High-velocity collimated outflows in planetary nebulae: NGC 6337, He 2-186, and K 4-47[1]

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ABSTRACT

We have obtained narrow-band images and high-resolution spectra of the planetary nebulae NGC 6337, He 2-186, and K 4-47, with the aim of investigating the relation between their main morphological components and several low-ionization features present in these nebulae.

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[1]Based on observations obtained at the 3.5-m New Technology Telescope (NTT) of the European Southern Observatory, and the at the 2.6-m Nordic Optical Telescope (NOT) operated on the island of La Palma by NOTSA, in the Spanish Observatorio del Roque de Los Muchachos of the Instituto de Astrofísica de Canarias, and with the NASA/ESA *Hubble Space Telescope*, obtained at the Space Telescope Science Institute, which is operated by AURA for NASA under contract NAS5-26555.

The data suggest that NGC 6337 is a bipolar PN seen almost pole on, with polar velocities of ≥ 200 km s^{-1}. The bright inner ring of the nebula is interpreted to be the "equatorial" density enhancement. It contains a number of low-ionization knots and outward tails that we ascribe to dynamical instabilities leading to fragmentation of the ring or transient density enhancements due to the interaction of the ionization front with previous density fluctuations in the ISM. The lobes show a pronounced point-symmetric morphology and two peculiar low-ionization filaments whose nature remains unclear.

The most notable characteristic of He 2-186 is the presence of two high-velocity ($\geq$135 km s^{-1}) knots from which an S-shaped lane of emission departs toward the central star.

K 4-47 is composed of a compact core and two high-velocity, low-ionization blobs. We interpret the substantial broadening of line emission from the blobs as a signature of bow shocks, and using the modeling of Hartigan, Raymond, & Hartman (1987), we derive a shock velocity of $\sim$150 km s^{-1} and a mild inclination of the outflow on the plane of the sky.

We discuss possible scenarios for the formation of these nebulae and their low-ionization features. In particular, the morphology of K 4-47 hardly fits into any of the usually adopted mass-loss geometries for single AGB stars. Finally, we discuss the possibility that point-symmetric morphologies in the lobes of NGC 6337 and the knots of He 2-186 are the result of precessing outflows from the central stars.

Subject headings: planetary nebulae: individual (NGC 6337, He 2-186, K 4-47) - ISM: kinematics and dynamics - ISM: jets and outflows

1. Introduction

Ionized gas in planetary nebulae (PNe) expands with typical velocities between 10 and 40 km s^{-1} (cf. Weinberger 1989; Corradi & Schwarz 1995), values which are similar or only slightly larger than those of the winds from their AGB progenitors, indicating moderate acceleration of the gas during the PN phase. Some PNe, however, exhibit expansion velocities an order of magnitude larger (100 – 500 km s^{-1}) and are generally associated with collimated outflows, such as bipolar PNe (cf. Corradi & Schwarz 1995) or jets (e.g., Bryce et al. 1997; Schwarz et al. 1997). These high-velocity, collimated outflows are usually best observed in the light of low-ionization species such as the [N ɪɪ] 658.3 nm line. The dynamical mechanisms collimating and accelerating the gas to the high velocities observed are not yet clear (García-Segura et al. 1999, Soker 1997).

In this paper, we present a morphological and kinematical study of three PNe (NGC-6337, He 2-186, and K 4-47) in which we also found the occurrence of bipolar outflows expanding with notably high velocities. This work is part of an observational program aimed at studying small-scale, low-ionization structures in PNe, such as knots, bullets, filaments, ansae, etc. These structures are very puzzling morphological components of PNe (Balick et al. 1998, and references therein). Most of the targets of our program were selected by Corradi et al. (1996b) by computing ([N ɪɪ]+Hα)/[O ɪɪɪ] ratio maps in the image catalogs of Schwarz, Corradi, & Melnick (1992) and Gorny et al. (1999). Results for four PNe were reported in two previous papers (Corradi et al. 1997; Corradi et al. 1999). In brief, some of the low-ionization features appear to be associated with extended jets (NGC 3918, and K 1-2) or with multiple collimated outflows (IC 4593 and Wray 17-1) characterised by moderate to high expansion velocities. In this paper, we discuss the properties of the low-ionization features in NGC 6337, He 2-186 and K 4-47.

2. Observations

Images and long-slit spectra of NGC 6337 (PN G349.3-01.1), were obtained on 1996 April 27 at ESO's 3.5-m New Technology Telescope (NTT) at La Silla (Chile), using the EMMI multimode instrument. With the TEK 2048^2 CCD ESO#36, the spatial scale of the instrument was 0″.27 pix^{-1} both for imaging and spectroscopy. The central wavelength and full width at half-maximum (FWHM) of the [N ɪɪ] filter used for imaging are 658.8 nm and 3.0 nm, and those of the [O ɪɪɪ] filter 500.7 nm and 5.5 nm. Further details of the observations are listed in Table 1. As with spectroscopy, EMMI was used in the long-slit, high-resolution mode (Corradi, Mampaso, & Perinotto 1996a), providing a reciprocal dispersion of 0.004 nm pix^{-1}, and a spectral resolving power of $\lambda/\Delta\lambda$=55000 (5.5 km s^{-1}) with the adopted slit width of 1″.0. The slit length was of 6 arcmin. The echelle order selected by using a broad Hα filter includes the He ɪɪ line at λ=656.01 nm, Hα at λ=656.28 nm, and the [N ɪɪ] doublet at λ=654.81 and 658.34 nm. The slit was positioned through the center of the nebula at position angles P.A.=−39° and P.A.=−75° (see Table 1).

He 2-186 (PN G336.3-05.6) was observed at the NTT on 1991 April 26 also with the EMMI instrument. Two medium-resolution spectra centered on Hα were obtained with grating #6, using a 2×2 binning of the CCD so that the spatial scale was of 0″.70 and

the spectral reciprocal dispersion 0.08 nm per binned pixel, corresponding to a resolving power of 4000 (75 $km\,s^{-1}$). The slit width was $1''.0$. The spectral range covered includes Hα, He II, the [N II] doublet, as well as the [S II] doublet at λ=671.6 nm and 673.1 nm. We also retrieved images of He 2-186 from the *HST* archive obtained on 1999, February 7 with the WFPC2 camera (PC CCD, $0''.0455$ pix^{-1}) in the [N II] F658N narrowband filter (659.0/2.9 nm). Two images of 400 and 200 sec exposure time, were combined to improve the S/N ratio and remove cosmic rays.

K 4-47 (PN G149.0+04.4) was observed at the 2.6-m Nordic Optical Telescope (NOT) of the Observatorio del Roque de los Muchachos (La Palma, Spain). Images were taken on 1997 September 20 and October 21, using the ALFOSC instrument and a Loral 2k × 2k CCD, providing a scale of $0''.19$ per detector pixel. The central wavelength and FWHM of the filters used at the NOT, corrected for the temperature at the time of observations, were: 500.9/3.0 nm ([O III]), 650.3/2.8 nm (Hα off-band), 656.4/0.8 nm (Hα), 658.5/0.9 nm ([N II]), and 672.0/5.0 nm ([S II]). Finally, a high resolution spectrum of K 4-47 was obtained using the echelle spectrograph IACUB (McKeith et al. 1993) on 1998 January 17. The detector was a Thompson THX31156 1024 CCD, giving a spatial scale of $0''.28$ per pixel and a reciprocal dispersion of 0.005 nm per pixel. The slit width was $0''.8$, providing a spectral resolution of 25000 (12 $km\,s^{-1}$). Exposure times and slit position angles are given in Table 1.

Images and spectra were reduced in a standard way using MIDAS and IRAF.

3.   NGC 6337

According to the literature, NGC 6337 is a multiple shell planetary nebula (e.g., Stanghellini, Corradi, & Schwarz 1993). Its distance, determined by statistical methods, is in the range of 1.1 to 1.7 kpc (Acker et al. 1992). Physical parameters for the nebula are also derived from statistical studies spread in the literature (see, for instance, Górny, Stasińska, & Tylenda 1997; Phillips 1998). The connection between the central star evolution and the morphology of NGC 6337 was studied by Stanghellini et al. (1993), who classified it as an elliptical nebula with multiple shells showing two axes of symmetry for the external structures. To our knowledge, no detailed kinematical studies of NGC 6337 exist.

Our [N II] and [O III] NTT images of NGC 6337 are presented in Fig. 1, together with the [N II]/[O III] ratio map.

3.1.   Morphology

The main morphological component of NGC 6337 is a circular ring. In [O III] the inner and outer radii of the ring are $14''$ and $24''$, respectively, the surface brightness peaking at $20''$ from the central star. In [N II] the ring is broken into filamentary structures which are aligned along the radial direction from the central star. Most of the [N II] emission is concentrated outside the [O III] peak radius, and shows extended, outward tails which are neatly enhanced in the [N II]/[O III] ratio map. The most prominent of these low-ionization radial features is labeled as C in the [N II] image of Figure 1.

The ring is surrounded by a faint halo. In [O III] this halo has a pretty uniform surface brightness and the shape of two "spiral arms"

bending clockwise toward the NW and SE directions. In [N ɪɪ], the halo is more irregular, and exhibits two peculiar bright filaments, labeled A and B in Figure 1. While B is in rough radial alignment with the central star, A is almost perpendicular to the radius from the central star. The maximum diameter of the halo is 120″.

3.2. Kinematics

The long slit of the spectrograph was positioned through the central star at P.A.=$-75°$, covering the low-ionization feature C, and at P.A.=$-39°$, throughout filament B and intersecting a portion of A (see Fig. 1). Spectra are shown in Figure 2. Hα and [N ɪɪ] velocities along the slit were measured by Gaussian fitting and are also presented in Figure 2.

At both position angles, the most notable feature is the presence of faint high-velocity halo components which appear located, in projection, both inside and outside the bright ring. These components span a radial velocity range of ~400 km s^{-1}. The overall shape of the nebula and of the velocity field is reminiscent of that of a bipolar nebula seen almost pole on, the bright ring being the projection of the equatorial density enhancement, which possibly collimates the high velocity outflow (cf. the mildly inclined PN Hb 5 (Corradi & Schwarz 1993b) and with the pole on bipolar PN K 4-55 (Guerrero, Manchado, & Serra-Ricart 1996) which also exhibits the striking "spiral arm" morphology of the halo of NGC 6337). ¿From the symmetry of the velocity field, we derive a heliocentric systemic velocity $V_{\rm sys}$=-70 ± 4 km s^{-1}, in excellent agreement with the measurement of -71 ± 4 km s^{-1} by Meatheringham, Wood, & Faulkner (1988).

Filaments A and B have radial velocities of ~-40 km s^{-1} and ~$+60$ km s^{-1}, respectively, with respect to the systemic velocity. Their velocities are not peculiar with respect to the surrounding gas, in the sense that they follow the overall Hα and [N ɪɪ] kinematic behavior which characterizes the emission from the diffuse halo and ring. At the position of A intersected by the slit, the [N ɪɪ] line broadens to 0.034 nm FWHM (corrected for the instrumental profile), compared to 0.019 nm in the surrounding gas. Along B, the line profile is also slightly broadened (0.026 nm), or split into two components separated by ~15 km s^{-1}.

It is difficult to determine the real 3-D geometry of the bright ring. That it is merely the projection on the sky of a spheroidal shell seems to be unlikely, since we do not observe the typical elliptical kinematical figure expected for such a geometry. The Hα and [N ɪɪ] velocity pattern in the ring at both position angles, however, is quite complex, and in its innermost regions both the Hα and, to a lesser extent the [N ɪɪ] lines, are split into two components separated by up to 50 km s^{-1} (see also Fig. 3). This clearly suggests that the ring is not thin, but is instead a thick structure or an "equatorial bulge" as observed in several bipolar PNe (e.g., M 1-28, K 3-46, K 3-72, and NGC 650-1; cf. Corradi & Schwarz 1995). The small difference in radial velocity from one side of the ring to the other indicates that the structure has a low inclination with respect to the plane of the sky, supporting the hypothesis that the nebula is seen almost pole on.

Line profiles are also composite through the radial filament C (Fig. 3), but no peculiar velocities are found as compared to the ring emission at P.A.=$-39°$, where no low-ionization features are present. Note that the

innermost part of C is also slightly visible in [O III], suggesting a real density enhancement.

3.3. Discussion: the large-scale structure

The present data reveal, for the first time, the existence of a high-velocity ($\geq 200 \ \mathrm{km \, s^{-1}}$) outflow in NGC 6337. According to the images and spectra, and considering the similarity with K 4-55 (Guerrero et al. 1996), the most likely interpretation is that these high-velocity components represent the polar expansion velocities of a bipolar PN seen almost pole on, the bright ring being the denser ionized in the equatorial plane (a thick ring or a "bulge") from which two symmetrical lobes depart.

The high velocities observed, one order of magnitude larger than those typical of PNe, are nevertheless not unusual among bipolar objects (Corradi & Schwarz 1995). Also the "spiral arms" observed in the [O III] image of NGC 6337 (and in K 4-55) might correspond to the point-symmetrical distribution of light emission which characterizes the lobes of several bipolar PNe seen more edge on (e.g, Hb 5, and NGC 6537; Corradi & Schwarz 1993b). In different nebulae, we would then observe the same overall helical geometry but from different points of view. The origin of this "secondary" point-symmetrical brightness distribution within the "primary" axisymmetrical geometry of the bipolar lobes has rarely been discussed in the literature. Pioneering work was done by Pişmiş, who, 25 years ago, proposed the occurrence of episodic, highly collimated and magnetized ejecta from diametrically opposed active spots, in hot stars and PN nuclei (Pişmiş 1974; see also Recillas-Cruz & Pişmiş 1981). More recently, the occurrence of collimated, high-velocity

and point-symmetrical outflows was ascribed to the action of fast winds from precessing accretion disks in binary systems (e.g., Schwarz 1992b). Cliffe et al. (1995) presented a gas-dynamical model in which this kind of morphology is reproduced as the result of a precessing jet interacting with circumstellar material. In their view, the precessing jet would correspond to the brighter point-symmetrical component of the nebula, while the axisymmetrical bipolar lobes would be the merging of the bow-shocks of individual jet segments. Can this scenario be applied to all bipolar PNe with a point-symmetrical brightness distribution within lobes? Considering the sample of bipolar PNe in Corradi & Schwarz (1995), and including other recent work on individual objects, it appears that about 30% of all bipolar PNe show a more or less pronounced point-symmetry in the surface brightness of the lobes. Except for special cases (such as NGC 6309, Schwarz et al. 1992, and perhaps He 2-186, see Sect. 4), the point-symmetrical light distribution in those bipolar PNe seems less pronounced than that displayed in figure 2 of Cliffe et al. (1995). Further and more complete modeling is clearly needed, and in particular the resulting velocity field, which might contain characteristic signatures of the precessing jet model, should be worked out. This is a very interesting issue, since should it turn out to be true, we would end with the quite unexpected conclusion that the overall bi-lobal shape of a significant fraction of bipolar PNe is the product of the dynamical interaction of precessing jets ejected by the central stars with the ambient medium. This is in contrast with the usual scenario of interacting-winds theories, in which the bipolar lobes are a result of the aspherical propagation of the shock driven by an (even isotropic) fast wind starting from

a very flattened AGB mass deposition (cf. Mellema 1997). Modeling along the lines of the interacting winds theory is presented by Garcia-Segura (1997, and private communication), who includes the effects of magnetic fields, stellar rotation, and precession of the central star induced by wide companions: as a result, precessing jets and point-symmetric nebular shapes are formed. Further modeling along this line is desirable.

3.4. Discussion: the low-ionization features

In the halo of NGC 6337, there are two peculiar low-ionization filaments, labeled A and B in Fig. 1, whose nature is unclear. As discussed in the preceding sections, they have velocities similar to those of their environment, which indicates that they might be the result of in-situ Rayleigh–Taylor and Kelvin–Helmholtz instabilities occurring in the "lobes" of the nebula (see Jones, Kang, & Tregillis 1994, for a discussion of the characteristic timescales). Their position in the kinematic plots, however, would indicate that they are not located along the polar axis of the bipolar nebula, but rather at intermediate latitudes on the "sides" of the lobes.

In the inner ring, there are a number of radial filaments, particularly clear in the [N II]/[O III] ratio image, the most pronounced one being labeled C. Following the fact that this feature is also slightly visible in [O III], it could be a real density enhancement. The irregular shape of the ring and the low-ionization radial filaments might then be the result of density inhomogeneities in the circumstellar density distribution. The interaction between the ionization front and the previously formed density fluctuations can produce the radial tails. The idea, explored

by Soker (1998), is that the ionization front will first form an ionization shadow, which looks like a tail pointing outward, and as a secondary consequence, a real condensation, due to the shock compression driven into the tail by the higher pressure of the surroundings. However, on short time scales the photoionization in the condensation can smooth out the density inhomogeneity, and therefore these kinds of structures should be considered as transient features. An alternative explanation for the formation of radial filaments was described by García-Segura & Franco (1996). It is based on the presence of dynamical instabilities of radiative shocks, which would lead to the fragmentation of the shell without involving previous density inhomogeneities. In this case, the presence of the ionization front exacerbates the growth of the instabilities, so that the resulting filamentary radial structures are not expected to be transient features. The model proposed by Dyson et al. (1993) for the low-ionization structures at small- and intermediate-scales of the Helix nebula (NGC 7293) might also apply. According to this model, radially aligned filamentary structures can be generated as an effect of the interaction of the post-AGB wind, in the supersonic and subsonic velocity regimes, with dense pre-existing clumps in the AGB wind. Within this kind of models, short and stubby tails as well as long and thin ones can be formed, but the details of these processes are still to be worked out numerically.

4. He 2-186

He 2-186 is a small, poorly studied southern PN. Hα+[N II] and [O III] images are presented in the catalog of Schwarz et al. (1992), which first revealed the existence of a pair of low-ionization knots detached from the core

of the nebula. A preliminary report on the high-velocity nature of these knots was given in Schwarz (1993) and Corradi, Schwarz, & Stanghellini (1993). The statistical distance for this object is in the range of 3.5 to 8.2 kpc (Zhang 1995; Acker et al. 1992).

4.1. Morphology

We show in Fig. 4 the [N II] HST image of He 2-186. The main body of the nebula is composed of several bright arcs of emission, which appear as the limb-brightnened projection of hollow bubbles, with two "conical" extensions roughly along the EW direction. Along P.A.=+30° and detached from the main shell of the nebula, there are two bright, elongated knots, which are labeled A and B in Fig. 4 and are partially connected to the core by an S-shaped lane of emission. This lane is in turn partially resolved into knots. In the ground-based image by Schwarz et al. (1992), all these features appear to be embedded in a diffuse nebulosity. The separation of the knots is of $8''.9$, and they are also observed in the higher-ionization species of [O III] (see Schwarz et al. 1992), but are considerably fainter.

4.2. Kinematics

The spectrograph slit of NTT was passing both through the center of the nebula and the knots (P.A.=−150°), and approximately along the long axis of the main body of the nebula (P.A.=−92°), as indicated in Fig. 4. The [N II] and Hα spectra are shown in Fig. 5; the [S II] doublet is not shown, since it is nearly identical to [N II] but fainter. Hα and [N II] velocities measured by Gaussian fitting are also presented in Figure 5. From the symmetry of the position–velocity plot, we adopt a heliocentric systemic veloc-

ity V_{sys}=−81±8 km s^{-1}, in agreement with the value of −87±15 km s^{-1} measured by Beaulieu (1997), and somewhat higher than the value of −67±9 km s^{-1} quoted in Schneider et al. (1983) .

Like NGC 6337, He 2-186 shows large expansion velocities. Knots A and B are redshifted and blueshifted, respectively, by ∼135 km s^{-1} with respect to the systemic velocity. The S-shaped lane of emission which extends toward the core is partially recorded in the spectrum at P.A.=−150°, and exhibits radial velocities which slightly decrease inwards from the values measured at the knots' positions. The same spectrum, however, also shows a peculiar velocity component with reversed redshift/blueshift as compared to the knots and showing a linear and continuum increase with radius of radial velocities up to the value of ±45 km s^{-1}. This component is not identified in the HST image, although it can in principle be associated with the diffuse nebulosity embedding the core and knots which is observed in the images of Schwarz et al. (1992). Extending out to the the radial distance of the knots, this second velocity component clearly indicates that the nebula of He 2-186 has a complex 3-D structure of which we see in projection two kinematical components.

There is additional spectral features which render the picture even more complex. The spectrum at P.A.=−92° shows that the Hα and [N II] emission extend much farther than expected from the image, out to at least 10″ from the center. In addition, in that spectrum there are a pair of opposite symmetrical features at ∼±130 km s^{-1} and about $1''.9$ from the center. Due to the lower spatial resolution of the NTT spectra (about $1''.4$ along the direction of the 1″ wide slit), and considering

seeing and tracking effects, it is difficult to identify these velocity components with features in the HST image.

4.3. Discussion

If we consider the knots and their S-shaped connection to the core by themselves, the present data would suggest that the knots of He 2-186 are at the leading tip of an extended, bent, highly collimated and high-velocity outflow. This is indicated by the S-shaped morphology of the knot–core connection and of its velocity pattern. The most likely cause of the bending would be precession of the collimating source. Again, models like that of Cliffe et al. (1995) or García-Segura (1997) might apply in this case.

Spectroscopy, however, unveils other components, and renders the situation more difficult to fit into the above scenario. The additional velocity components extending as far as the knots but with reversed redshift clearly indicate that the extended outflow of He 2-186 has a complex 3-D shape. The gross morphology of the velocity field is somewhat reminiscent of that of the "Southern Crab", the nebula around the symbiotic star He 2-104 (Corradi & Schwarz 1993a), which possesses a bipolar nebula with prominent polar jets (cf. Fig. 3 in Corradi & Schwarz 1993a and Fig. 5 in this paper). It might be that He 2-186 is a similar object poorly resolved. Alternatively, as discussed for NGC 6337 in Sect. 3.3, the knots and lanes of He 2-186 might be prominent point-symmetrical features within an overall structure consisting of (faint) hollow bipolar lobes.

5. K 4-47

K 4-47 is an almost unstudied northern PN. No previous individual studies exist in the literature apart from measurements in radio or infrared surveys. This PN is associated with the *IRAS* source 04166+5611 and shows 5-GHz radio emission (Aaquist & Kwok 1990). Cahn, Kaler, & Stanghellini (1992) give a statistical distance of 8.5 kpc. Using another statistical method, Zhang (1995) obtained a distance of more than 20 kpc (and van de Steene & Zijlstra (1994) give an upper limit of 26 kpc); these are unrealistic values putting the nebula well outside the boundaries of the Galaxy (see the discussion in the following sections).

5.1. Morphology

The narrow-band images in Fig. 6 reveal that K 4-47 consists of an emission-line core and two diametrically opposite blobs aligned at P.A.=+41°. The blobs are prominent in the low-ionization lines of [N II] and [S II], visible in Hα, and absent in [O III], while the core is of relatively higher excitation, showing bright [O III] emission. A faint lane of emission connects the blobs to the core. The blobs and core are practically unresolved in our image, and have a FWHM only slightly larger than the seeing value (0.″8). The blobs are not symmetrically located with respect to the core, the northern one being at larger projected distance than the southern one (see Table 2). Continuum emission is detected neither in the core nor in the knots in our Hα off-band image (not presented here).

Our images also suggest the existence of other small differences in the spatial location of the core and the blobs, such as a displacement of 0.″3 southwest of the Gaussian cen-

troid of the core in [N II] with respect to Hα. The [N II] center of the southern blob also seems to lie about $0''.2$ more southwest than in Hα and [S II], but these latter findings should be confirmed by new imaging with better resolution and high astrometric quality.

5.2. Kinematics

The echelle spectrum at P.A.=+41° is shown in Fig. 7, together with the heliocentric Hα and [N II] velocities measured by Gaussian fitting along the slit. Radial velocities and line widths for the blobs are also reported in Table 2.

The gross kinematic figure is that of a linear increase of radial velocities from the core to the blobs, but several peculiar kinematic features are also observed, especially in Hα. The velocity separation of the two blobs is 105 km s^{-1} in Hα and 115 km s^{-1} in [N II] (note that this difference is larger than the measurement errors). Line profiles at the positions of the blobs are roughly Gaussian and are significantly broadened, with a FWHM, corrected for the instrumental profile, of 75-90 km s^{-1} (see Table 2).

The Hα radial velocities are systematically redshifted around the core position as compared to the [N II] ones, by up to 30 km s^{-1}. This difference is noticeable, and together with the displacement of the Hα peak position from the [N II] one, seen in the images, suggests the existence of two distinct flows of matter with different geometries and/or velocities, one bright in Hα and the other with enhanced [N II] emission. In this respect, note also the peculiar kinematic feature, detected in Hα $1''.5$ southwest of the core, which has a radial velocity of $\sim +70$ km s^{-1} with respect to the central region and shows sign reversal with respect to the collimated outflow of the

blob on the same side of the nebula.

The complex kinematics in the innermost regions also makes it difficult to estimate the systemic velocity of the nebula, and compute the expansion velocity of each blob separately. If we take the average radial velocity of the blobs as the heliocentric systemic velocity of K 4-47, we obtain a value of -32 km s^{-1}. If we instead assume that the different distances from the center of each blob just reflect different initial velocities of coeval ejecta, the requirement of proportionality between distance and velocity would imply a systemic velocity of -42 km s^{-1}. We adopt a mean value, $V_{sys}=-37\pm10$ km s^{-1}, as the heliocentric systemic velocity of K 4-47, the large error reflecting the above uncertainties.

According to both imaging and spectroscopy, the separation of the two blobs at peak emission of Gaussian fitting is of $7''.5\pm0''.1$ in the bright [N II] line.

5.3. Discussion

K 4-47 is composed of a bright emission-line core exhibiting complex kinematics. Departing from the core, a highly collimated outflow ending in two low-ionization blobs is detected. The velocity separation of the blobs projected onto the line of sight is around 110 km s^{-1}, and their [N II] and Hα line profiles are substantially broadened (75 – 100 km s^{-1} FWHM).

The blobs might be the tips of jets interacting with the ambient medium, or bullets of dense gas ejected from the central star and expanding at considerable velocities. If so, radiating bow-shocks are expected to form. Hartigan et al. (1987) constructed line profiles for shocked–ionized bullets, whose line widths are shown to be a direct measure of the shock velocity. Using their prescriptions,

and correcting the observed line widths for instrumental and thermal broadening (assuming T_e=10000 K and zero turbulent velocity), we obtain shock velocities between 125 and 155 $\mathrm{km\,s^{-1}}$, depending on the blob and the line (Hα or [N II]) considered. Assuming that blobs are expanding through a stationary circumstellar medium (the interstellar medium or the slowly expanding remnant of the red-giant wind), the shock velocity is nothing but the expansion velocity of the blobs, and from the observed projected velocities we derive an inclination of the outflow to the line of sight of 65°–70°. According to Hartigan et al. (1987), such a mild inclination to the plane of the sky and the computed shock velocity around 150 $\mathrm{km\,s^{-1}}$ would yield quite symmetric integrated line profiles, as is indeed observed in the spectra of the blobs of K 4-47. Note however that the main difference from the models by Hartigan et al. (1987) is that in the case of K 4-47 the ionization balance in the blobs might be dominated by the energetic radiation from the central star, whereas their models are for purely shocked–ionized bullets such as H–H objects.

The distance to K 4-47 is unknown, and considering the peculiar morphology of the nebula, standard statistical methods are likely to give completely unreliable results. We could estimate rough limits on the distance to K 4-47 by assuming that it participates in the general circular rotation around the Galactic center. With a standard Galactic rotation curve and with the adopted systemic velocity of -37 ± 10 $\mathrm{km\,s^{-1}}$, the kinematical distance of K 4-47 is constrained between 3 and 7 kpc. Note that a distance larger than 7 kpc is unlikely, since K 4-47 is located nearly in the direction of the Galactic anticenter (l=149°), and larger distances would position the neb-

ula in very peripheral regions of the Galaxy (the truncation radius of the volume density of stars in the Galaxy is often assumed to be around 15 kpc, cf. Wainscoat et al. 1992).

With these distance limits, and using the orientation and kinematic figures above, the linear size of K 4-47 would be ∼0.1 pc for a distance of 3 kpc, and ∼0.3 pc for 7 kpc. The age of the blobs would be ∼400 yr or ∼900 yr, for the short and long distances, respectively.

K 4-47 shares several similarities with the PN M 1-16 (Schwarz 1992a, Corradi & Schwarz 1993c; Aspin et al. 1993), in which a shocked, highly collimated and high-velocity outflow was also detected. In M 1-16, the outflow is resolved into a pair of bipolar lobes ending in a series of relatively bright knots. Imaging with *HST* resolution would be needed to resolve similar structures in K 4-47 if they existed.

6. Conclusions

A morphological and kinematical study of the PNe NGC 6337, He 2-186, and K 4-47 is presented. All three nebulae show gas expanding at large velocities (130–200 $\mathrm{km\,s^{-1}}$). These high-velocity outflows define the main collimation axis of the ejecta.

In the case of He 2-186 and K 4-47, the high-velocity outflows correspond to a pair of opposed symmetrical, low-ionization knots detached from the cores of the nebulae. Evidence of strong shocks is found in the knots of K 4-47, which might be one of the causes of the enhancement of the emission from low-ionization species. Low-resolution spectra, as well as detailed modeling taking into account all the different mechanism which play a role in the production of spectral lines (abundances, physical properties, shocks, and pho-

toionization from the central star) are clearly needed. In any case, the mass-loss scenario which is derived from the present observations is quite peculiar, especially for K 4-47. In this object, and in similar ones (e.g., M 1-16, Schwarz 1992a), all the ionized mass appears to be contained in the compact core and in the high-velocity blobs. Fast-moving bullets and jets have been observed also in other PNe (e.g., NGC 3918, Corradi et al. 1999), but generally they are secondary morphological structures as compared to the main shells of the nebulae. In K 4-47, on the contrary, the core–jets–blobs constitute the whole nebula. Is the *entire* AGB envelope constrained to flow within such a small solid angle? The interacting-winds models of Icke et al. (1992) and García-Segura et al. (1999) are able to explain the formation of highly collimated nebulae, starting from torus-like initial density distributions or in the presence of significant magnetic fields, but it is not clear whether they can reproduce extreme morphologies such as those of K 4-47 and M 1-16. An alternative hypothesis, is that objects like K 4-47 are not genuine PNe, but are the results of (sporadic?) mass loss from interacting binary systems. There, accretion disks are expected to provide the conditions for extreme collimation of the outflows. In erupting systems, such as symbiotic stars (see Corradi et al. 1999 for a discussion of the properties of the outflows from this class of object), high velocity winds from the accreting components are also expected. Thus it will be important to investigate in depth the nature of the central star of K 4-47 and similar objects, searching for possible signatures of binarity.

In the case of NGC 6337, the highest velocities measured (200 $km\,s^{-1}$), which are thought to occur in the polar regions of bipo-

lar lobes seen almost pole on, are not associated with the outer low-ionization filaments observed in [N II]. The location, shape and velocities of these outer filaments pose a difficult problem in order to explain their origin. The low-ionization knots and tails observed in the bright "equatorial" ring are instead interpreted as being the result of initial dynamical instabilities which lead to fragmentation of the ring and which are enhanced by the ionization front (according to the modeling of García-Segura & Franco 1996), or, on the other hand, transient density enhancments due to the interaction of the ionization front with previous density fluctuations in the ISM (Soker 1998).

Finally, both the point-symmetrical morphologies of NGC 6337 and He 2-186 strengthen the idea of the occurrence of precessing outflows in PNe, a hypothesis that has found more and more observational support in the recent years (e.g., Schwarz 1992a; Lopez, - Meaburn & Palmer 1993; Guerrero & Manchado 1998), and which also naturally leads to the idea of the existence of binary systems as the central stars of these nebulae. Embarrasingly, in spite of the numerous high-quality data which are presently available it remains mysterious why these point-symmetrical features are often found within bipolar lobes with an overall axisymmetrical geometry. Clearly, some basic piece of the puzzle of the PN formation and evolution is still missing.

7. Acknowledgments

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Fig. 1.— The NTT images of NGC 6337, on a logarithmic intensity scale. Above: the [O III] image, at different intensity levels to highlight both the inner ring of the nebula (left) and its faint 'spiral-shaped' halo (right). Below: the [N II] image and the [N II]/[O III] ratio map. The locations of the slit used for spectroscopy are indicated in the [N II] image by short lines on either side of the object.

Fig. 2.— Left: the NTT long-slit spectra of NGC 6337, on a logarithmic intensity scale. The faint emission to the left of Hα is an He II line at λ=656.01 nm. Right: radial heliocentric velocities computed by Gaussian fitting of the Hα (empty circles) and [N II] (full circles) lines. The dotted vertical line is the adopted systemic velocity.

Fig. 3.— Details of the images (the two leftmost boxes) and of the spectrum at P.A.=−75° (the three rightmost boxes) of NGC 6337 for the region around the low-ionization feature C. The images have been rotated so as to have the slit location along the vertical direction and to allow for direct comparison with the spectra. Velocities are as in Figure 2.

Fig. 4.— The [N II] HST image of He 2-186, on a logarithmic intensity scale, and with different intensity cuts for the inner and outer regions of the nebula. The locations of the slit are indicated by lines on either side of the object. We also mark distances of 5″ from the center along the slit directions, to facilitate comparison with the spectra in Fig. 5.

Fig. 5.— Left: the spectra of He 2-186 on a logarithmic scale. Right: measured Hα (empty circles) and [N II] (full circles) radial velocities, corrected for the adopted systemic velocity of the nebula.

Fig. 6.— The NOT images of K 4-47 on a linear scale.

Fig. 7.— Left: the spectrum of K 4-47 at P.A.=+41° on a linear scale. Right: heliocentric Hα (empty circles) and [N II] (full circles) radial velocities.

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TABLE 1

LOG OF THE OBSERVATIONS

Object	Telescope	Filter (exposure time, min)	Seeing
		Images	
NGC 6337	NTT	[N II] (4), [O III] (2)	0″.9
K 4–47	NOT	[N II] (10), Hα (10), Hα cont. (5), [S II] (10)	0″.8
		[O III] (10)	0″.9
		Long–slit spectra	
		P.A. (exposure time, min)	
NGC 6337	NTT	−39° (60), −75° (30)	0″.9
He 2-186	NTT	−150° (5), −92° (5)	0″.9
K 4-47	NOT	41° (60)	∼1″

TABLE 2

DISTANCES, VELOCITIES AND LINE WIDTHS FOR THE
KNOTS OF K 4-47.

	d [″]		V_r [km s^{-1}]		FWHM [km s^{-1}]	
	Hα	[N II]	Hα	[N II]	Hα	[N II]
South	3.1	3.0[a]	−86	−89	88	75
North	4.2	4.5[a]	20	28	99	82

[a]From both imaging and spectroscopy.

NOTE.—d is the apparent distance measured in the image from the peak emission of the core, V_r the measured heliocentric velocity, and FWHM the full width at half maximum of line emission corrected for the instrumental profile.

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